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Assessment of the status of the development of the standards for the Terrestrial Essential Climate Variables

GTOS

Essential Climate Variables

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Table of Contents

List of Acronyms

ALOS	Advanced Land Observation Satellite
ASAR	Advanced Synthetic Aperture Radar
BCEF	Biomass Conversion and Expansion Factors
DESDynI	Deformation, Ecosystem Structure and Dynamics of Ice
ECV	Essential Climate Variable
ENVISAT	ENVironmental SATellite
ERS	Earth Resources Satellite
ESA	European Space Agency
FAO	Food and Agriculture Organization of the United Nations
FAPAR	Fraction of Absorbed Photosynthetically Active Radiation
GCOS	Global Climate Observing System
GEO	Group on Earth Observations
GEOSS	Global Earth Observation System of Systems
GHG	Greenhouse Gas
GOFC-GOLD	Global Observation of Forest and Land Cover Dynamics
GTOS	Global Terrestrial Observing System
IGCO	Integrated Global Carbon Observation
IGOS	Integrated Global Observing Strategy
IPCC	Intergovernmental Panel on Climate Change
JAXA	Japan Aerospace Exploration Agency
JERS	Japanese Earth Resources Satellite
JRC	Joint Research Center of European Commission
LAI	Leaf Area Index
LCCS	Land Cover Classification System
LIDAR	Light Detection and Ranging
LULUCF	Land Use Land-Use Change and Forestry
MERIS	Medium Resolution Imaging Spectrometer
MODIS	Moderate Resolution Imaging Spectroradiometer
NASA	National Aeronautics and Space Administration
NFMA	National Forest Monitoring and Assessment
NOAA	National Oceanic and Atmospheric Administration
PALSAR	Phased Array type L-band Synthetic Aperture Radar
REDD	Reducing Emissions from Deforestation and Forest Degradation
SAR	Synthetic Aperture Radar
SOM	Soil Organic Matter
SOTER	Soils and Terrain Digital Database
SPOT	Satellite Pour l'Observation de la Terre
TM	Landsat Thematic Mapper
UNESCO	United Nations Educational Scientific and Cultural Organization
UNFCCC	United Nations Framework Convention on Climate Change

Executive Summary

Vegetation biomass is a crucial ecological variable for understanding the evolution and potential future changes of the climate system. Vegetation biomass is a larger global store of carbon than the atmosphere, and changes in the amount of vegetation biomass already affect the global atmosphere by being a net source of carbon, and having the potential either to sequester carbon in the future or to become an even larger source. Depending on the quantity of biomass the vegetation cover can have a direct influence on local, regional and even global climate, particularly on air temperature and humidity. Therefore, a global assessment of biomass and its dynamics is an essential input to climate change forecasting models and mitigation and adaptation strategies.

In addition there are two other emerging issues which contribute to the increasing importance of the biomass role as an essential climate variable: i) the growing use of biomass for energy production, so the increasing percentage of global greenhouse gases (GHGs) emitted from biomass consumption, and ii) the increasing concern on the possibility to significantly reduce global GHGs emissions by avoiding biomass losses from deforestation, forest degradation, and accounting for the effects of natural disturbances. This document will mainly address living terrestrial above-ground vegetation biomass, in particular woody biomass.

Biomass is defined as mass of live or dead organic matter. Changes in time of vegetation biomass per unit area (biomass density) can be used as an essential climate variable, because they are a direct measure of sequestration or release of carbon between terrestrial ecosystems and the atmosphere. In this document, when using the term "biomass" we refer to the vegetation biomass density, that is mass per unit area of live or dead plant material. Unit of measure is g/m2 or multiples. The carbon pools of terrestrial ecosystems involving biomass are conceptually divided into above-ground biomass, below-ground biomass, dead mass and litter.

Biomass can be measured by *in situ* sampling or remote sensing using the following methods:

i) *In situ* destructive direct biomass measurement: this method entails harvesting plants, drying them, and then weighing the biomass. Biomass measurements can be undertaken on a single-tree basis or on area (plot) basis. This is the most direct and accurate method for quantifying biomass within a small unit area. If optimised from scope of generated information, time and cost point of view, this method can be cost effective for the quality of the produced estimated on carbon. I*n-situ* measurements can be carried out on timber and non-timber exploitation sites on basis of reprehensive sample of the total population at large scale.

ii) *In situ* non-destructive biomass estimations: this includes measurements that do not require harvesting trees, such as height and stem diameter and uses allometry (see below) or conversion factors to extrapolate biomass to unit ground area. Nowadays, statistical methods and techniques of estimation of total living or dead woody volume and available conversion factors make it relatively easy to estimate living and dry biomass and carbon.

iii) Inference from remote sensing: remote sensing measures the amount of microwave, optical or infrared radiation that is reflected or scattered by the vegetation. This radiation can be related to different biomass levels of the vegetation via a direct relationship between the remotely sensed response or through indirect relationships, whereby attributes estimated from the remotely sensed data, such as leaf area index (LAI), structure (crown closure and height) or shadow fraction are used in equations to estimate biomass.

iv) Models: different models have been developed to derive biomass estimates over large areas incorporating spatial data (such as elevation and radiation), remotely sensed data, and field samples or forest inventory data.

Allometric equations are used to extrapolate both *in situ* and remotely sampled data to a larger area and to derive biomass from other variables. Allometry relates the size of one structure in an organism to the size or amount of another structure in the same organism; therefore it is possible to estimate biomass from diameter, height, age, etc., and extend the datum to a larger area with the same characteristics.

In situ measurements are critical to the monitoring of terrestrial carbon stocks. Combined with land use and vegetation cover change estimates, *in situ* data is unavoidable. *In situ* data can be obtained from national forest inventories or from case studies from representative samples of the forest ecosystems. National forest inventories are the most reliable sources of quality information to account national carbon stocks but on a variety of other biophysical and socio-economic forest and tree parameters covering products and services. *In situ* measurements should be conducted no longer than every five years, in order to reasonably detect biomass changes in time. *In situ* measurements, especially if standardised and with the needed accuracy, provide indispensable information for validation of satellite data, but, due to the required time and the potential impact on the environment, they are infeasible at large scale. On the contrary remotely sensed data provides a synoptic view of the area of interest that enables the estimation of biomass values over large areas. While satellite approaches to estimate biomass are becoming increasingly used, there are still limitations related to accuracy and range of predictions. However, satellite technology, when calibrated with ground data, allows for accurate biomass estimates based on increasingly frequent measurement of biomass. Further several satellite methods have demonstrated potential for providing direct and indirect global above-ground biomass information at high resolution (below 1km). With improved sensor capabilities combined with previous experience and methods, it is expected that satellite and model-based estimates of biomass will form the mechanism for the large area monitoring of biomass.

At least the following requirements need to be met to improve the reliability of biomass estimates and their utility for a better monitoring and understanding of climate change:

1. Follow the IPCC Guidelines for National Greenhouse Gas Inventories (2006) for standard *in situ* biomass measurements.
2. Promote the development of new standards for biomass products and harmonize the current different methodologies.
3. Improve the quality and quantity of *in situ* biomass estimates needed for remote sensing calibration and validation.
4. Develop methods for assessing uncertainty of biomass estimates and maps, in order to provide more reliable inputs to models.
5. Extend forest biomass inventories to tropical forests, non-commercial forests, mangroves, dry woodlands and under-represented regions, and increase the number of permanent plots and the periodicity of data collection.
6. Develop new or improved allometric functions (with associated description of the site chacteristics where the allometric functions were derived), along with an analysis of the error propagation effects that may occur during the scaling process.

7. Develop better and validated regional or national biomass conversion and expansion factors and carbon conversion factors.
8. More coordination is needed among the *in situ* and space based earth observation communities to move remote sensing assessments for biomass mapping to more operational mode.
9. Pursue a further development and integration of SAR and optical data to provide estimates of biomass in a synoptic manner over large areas.
10. Produce more accurate tree height measurements from LiDAR technology, calibrated with field samples (i.e. field laser), in order to improve the biomass estimates derived from allometry and the methods to incorporate these datasets into regional estimation and mapping.
11. For a more comprehensive picture of the total biomass in a stand, below-ground biomass, coarse woody debris, fine woody debris and litter mass should be also considered, and new soil carbon measurement techniques and sampling strategies should be developed.
12. *In situ* measurements for biomass should be conducted at least every 5 years, and remote sensing inference should be repeated at least on an annual basis.
13. A single classification system for remote sensing estimation of biomass should be adopted; a widely accepted standard is the Land Cover Classification System (LCCS) and its accepted translations for countries.

No international validated standards are already available for biomass estimation from remote sensing.

1. Introduction

Biomass plays two major roles in the climate system: (i) photosynthesis withdraws carbon dioxide (CO_2) from the atmosphere and stores it in plants as biomass, part of which is transferred to the soil when it decomposes or is stored in protected soil carbon pools; (ii) biomass burnt by fire emits CO_2, other trace gases and aerosols to the atmosphere. Also biomass affects other Terrestrial Essential Climate Variables, like Albedo (ECV T8), Land Cover (ECV T9), FAPAR (ECV T10), LAI (ECV T11), Biomass (ECV T12) and Fire disturbance (ECV T13). Therefore, a global assessment of biomass and its dynamics are essential inputs to climate change forecasting models and mitigation and adaptation strategies. Biomass estimates may range from local to global scales, and for some regions, particularly tropical forest regions, there are large variations in the estimates reported in the literature. Global and national estimates of forest above-ground biomass are often not spatialized, but rather compiled through the tabular generalization of national level forest inventory data. The general lack of accurate spatial forest biomass data has been considered one of the most persistent uncertainties concerning global C budgets (Harrell et al., 1995). To address this problem and to meet information commitments for reporting and modeling, extensive research into a wide-range of methods and data sources have been undertaken for generating spatially explicit estimates and maps of large-area biomass.

The importance of biomass as an Essential Climate Variable is due to both its role as a carbon sink during the process of photosynthesis, its role in governing ecosystem productivity and its growing use for generation of bioenergy. Sustainable management of biomass sources, in particular forests, which store most of the Earth's biomass, contributes to reduction of CO_2 in the atmosphere, mitigation of climate change and protection of other ecosystem services including biodiversity conservation and water resources. Estimates of biomass change (due to land use and management practices or natural processes) enable a direct measurement of carbon sequestration or loss (as long as associated changes in soil carbon are accounted for) that can help validate carbon-cycle models and to quantify the human induced impacts on global climate change. Carbon emission from deforestation is the largest source of greenhouse gas emissions in many developing countries. Reducing Emissions from Deforestation and Forest Degradation in Developing Countries (REDD) in Developing Countries could potentially achieve a reduction of 50 Gt of carbon until 2100 (Gullison et al. 2007). Within the circumpolar boreal, fire represents an important source of carbon emissions due to its alteration of biomass carbon stocks (Isaev et al. 2002; Turquety et al. 2007), although uncertainties remain on the share of C that is stored in stable forms (e.g. charcoal) during ignition of biomass and of soil organic matter (SOM). In addition to fire, other disturbance and natural hazards, such as large insect outbreaks, can also result in a transition of a forest from carbon sink to source. This suggests that future efforts to influence the carbon balance through forest management should consider also natural or anthropic disturbances (Kurz et al. 2008).

This document is mainly related to living terrestrial above-ground vegetation biomass, especially woody biomass. The below-ground component is still poorly known, because it can not be detected by remote observations and it needs labour- and time-intensive *in situ* measurements.

2. Definition and units of measure

Biomass is defined as mass of live or dead organic matter. Changes in time of vegetation biomass per unit area (biomass density) can be used as an essential climate variable, because they are a direct measure of sequestration or release of carbon between terrestrial ecosystems and the atmosphere. Therefore in this document, when using the term "biomass" we refer to the vegetation biomass density, that is mass per unit area of live or dead plant material. Unit of measure is g/m2 or multiples. Unit of measure is g/ m2 or multiples.

According to the IPCC Good Practice Guidance for LULUCF (2003), the carbon pools of terrestrial ecosystems involving biomass are conceptually divided into above-ground and below-ground biomass, dead mass and litter. These compartments are defined as follows:

Above-ground biomass: all living biomass above the soil including stem, stump, branches, bark, seeds, and foliage.

Below-ground biomass: all living biomass of live roots. Includes fine roots (< 2 mm diameter), small roots (2 – 10 mm diameter), and large roots (> 10 mm diameter). Fine roots are usually excluded because these often cannot be distinguished empirically from soil organic matter or litter, and the live biomass changes significantly seasonally.

Dead mass: includes all non-living woody biomass not contained in the litter, either standing, lying on the ground, or in the soil. Dead wood includes wood lying on the surface, dead roots, and stumps larger than or equal to 10 cm in diameter and greater than 1 m in length.

Litter: includes all non-living biomass with a diameter less than a minimum diameter chosen by a given country (for example 10 cm), lying dead, in various states of decomposition above the mineral or organic soil. The original material (e.g. needles) should still be identifiable to be considered litter. This includes the litter, fumic and humic layers. Live fine roots (of less than the suggested diameter limit for below-ground biomass) are included in litter or SOM when they cannot be distinguished from it empirically. Distinction between litter and soil components should be based on particle-size, e.g. 2 mm as recommended by IPCC (2006).

3. Existing measurement methods and standards

Only above-ground biomass is measurable with some accuracy at the broad scale. While below-ground biomass stores a large part of total carbon stocks, it is still poorly known because it can only be assessed through *in situ* measurements that tend to be labour- and time-intensive (particularly for forest ecosystems): currently in most of cases the below-ground component is derived from above-ground biomass.

There are four main ways to monitor biomass and combinations thereof, which are discussed in more detail below:

(a) ***In situ* destructive direct biomass measurement**;
(b) ***In situ* non-destructive biomass estimations (using equations or conversion factors)**;
(c) **Inference from remote sensing (experimental stage)**;
(d) **Models**.

Allometric equations are used to extrapolate both *in situ* and remotely sampled data to a larger area and to derive biomass from other variables. Allometry relates the size of one structure in an organism to the size or amount of another structure in the same organism; for example, computing wood volume or biomass from diameter and height of a sample of trees and applying the equation with dimensions of another tree to compute its volume or biomass (Hamburg et al., 1997: Ravindranath and Ostwald, 2008).

More simply the assessment of non-woody biomass, such as in grasslands and croplands, is generally based upon the root/shoot ratio since the above-ground biomass can be harvested entirely (Scurlock et al., 2002).

Allometric equations can be applied to one or more variables (such as tree height, diameter, age, and vegetation type or structure) derived from forest inventories or from remote sensing information. Published allometric equations for specific vegetation types and tree species are often used. Since the allometric coefficients vary between sites and species, and based on a certain range of tree diameters, the use of standard allometric equations can lead to significant errors in vegetation biomass estimations (Chave et al., 2005; Heiskanen, 2006). This problem occurs when allometric equations are applied to vegetation types that are outside the area where they were originally produced. As a consequence there has been efforts in developing generalized regional and national tree biomass equations that could be applied to a larger geographic footprint than most existing allometric equations (Schroeder et al., 1997; Lambert et al., 2005; Case and Hall, 2008).

(a) *In situ* destructive direct biomass measurement

This method entails harvesting trees (or shrubs, herbs, etc.), drying them, and then weighing the biomass. Biomass measurements can be undertaken on a single-tree basis or on plot area basis. In the first case the biomass of each individual is measured, whereas in the second case the total biomass of a specific area or sample plot is measured. While this is the most direct and accurate method for quantifying biomass within a small unit area, it can be time and resources consuming and infeasible at large scale. This method may also not yield representative area estimates when the results have to be spatially extrapolated. As a result, it is often used for specific research purposes and for developing biomass equations to be applied for estimating biomass on large scale. Additional data can be derived from the analysis of timber and fuelwood exploitation.

(b) *In situ* non-destructive biomass estimations

This method includes sampling measurements that do not require harvesting trees, such as height and trunk diameter (measured by clinometers, field laser, tree callipers and tapes) and uses allometry or conversion factors to extrapolate biomass to unit ground area. Among non-destructive biomass estimation techniques, biomass equations usually yields the most accurate estimates as long as the equations are derived from a large enough number of trees representative of the considered ecosystem type. Biomass equations can be developed for a single species or for a whole ecosystem type. Many different model approaches both linear and non-linear have been used (Satoo & Madgwick, 1982). If the biomass has been measured for sample plots rather than for individual trees, biomass equations can be established that relates plot biomass to plot characteristics, such as basal area, stand height, stem density, etc. When biomass equations are not available, conversion and expansion factors can be used in order to convert growing stock (cubic meters of stem volume of standing trees) to biomass, usually above ground but also below-ground. The 2006 IPCC Guidelines includes a number of default conversion and expansion factors for different types of forests and climatic zones. Most of the available biomass data are derived from the non-destructive sampling (i.e. national forest inventories), however often the lack of reliable biomass coefficients hinders an accurate biomass extrapolation.

(c) Inference from remote sensing

The advantage of biomass estimation approaches that incorporate some form of remotely sensed data is through provision of a synoptic view of the surface area of interest, thereby capturing the spatial variability in the attributes of interest (e.g., height, crown closure). The spatial coverage of large area biomass estimates that are constrained by the limited spatial extent of forest inventories may be expanded through the use of remotely sensed data. Similarly, remotely sensed data can be used to fill spatial, attributional, and temporal gaps in forest inventory data, thereby augmenting and enhancing estimates of forest biomass and carbon stocks derived from forest inventory data. Such a hybrid approach is particularly relevant for non-commercial forests where basic inventory data required for biomass estimation are lacking.

Remote sensing measures the amount of microwave, optical or infrared radiation that is reflected or scattered by the imaged area in the direction of the sensor. This amount is related to biomass levels of the vegetation in the imaged resolution cell at certain electromagnetic wavelengths. Generally, biomass is either estimated via a direct relationship between spectral response and field estimates of biomass using multiple regression analysis, k-nearest neighbour, neural networks, or through indirect relationships, whereby attributes estimated from the remotely sensed data, such as leaf area index (LAI), structure (crown closure and height) or image objects such as shadow fraction are used in equations to estimate biomass.

There are three main ways of estimating biomass from satellite or airborne data; when using remotely sensed data for biomass estimation, the choice of method often depends on the required level of precision and the availability of plot data. Some methods, such as k-nearest neighbour require representative image-specific plot data, whereas other methods are more appropriate when scene-specific plot data are limited.

The indirect method may use data such as from Landsat Thematic Mapper (TM) to determine the area of woody vegetation across a given scale, then stratifies the total area into classes that are relatively homogenous in terms of biomass (such as structural vegetation types), and then attributes an average biomass density (kg/ha) to each. The classification systems for vegetation must be based on attributes that are easy to discern from remotely sensed data, such as crown cover classes, genus and major species, growth form (tree, shrub, etc.) and height. In assigning an average biomass density to each stratum (vegetation class), it may be necessary to gather additional field data in order to validate that biomass estimates for a stratum in one part of a country or region are valid in another (Australian Greenhouse Office, 1999). As biomass density is affected by the stage of development, it may also be necessary to apply a factor to biomass estimates that account for different growth stages within strata. This approach is referred to as the look-up table approach because a biomass density is assigned to a stratum. An alternative approach that will yield more precise estimates is to derive estimates of forest composition and structure from the remote sensing image that can then be used as input to allometric equations for biomass estimation. Because allometric functions of biomass density will vary by species or dominant vegetative land cover, a pre-stratification of the image could improve the derivation of structure that are subsequently used as inputs to estimate biomass. In regions where in-situ data may be sparse, field information may be used with high spatial resolution satellite data for biomass estimation that can subsequently be scaled using k-nearest neighbour or other modelling methods. In total, there is more than one indirect method for biomass estimation.

The second method uses a process model to estimate the amount and distribution of biomass, predicted from known relational variables, to derive spatially continuous biomass estimates (Australian Greenhouse Office, 1999). For example, Graetz (1988) discerned a relationship between above- and below-ground biomass density and the annual mean soil moisture index. Also, estimating vegetation height from LiDAR (Light Detection And Ranging), or matching of multi view angle optical imagery, can provide an additional variable for driving spatially explicit allometric equations for biomass estimation.

The third method uses actively transmitted microwave sensors (SAR - Synthetic Aperture Radar). Microwaves interact with wet material such as leaves, branches and stems. The signal that is received by the sensor is related to vegetation biomass. There is, however, a saturation level whereby the received radar signal is no longer correlated with increased biomass anymore. The biomass where this saturation level occurs is higher for longer radar waves. Although this relationship is also dependent on other environmental parameters (such as soil moisture and roughness, canopy structure and others), it has been shown that areas of millions of square kilometres of forest can be mapped for biomass stocks using radar satellites (Balzter et al. 2001, Wagner et al. 2003). Apart from using the signal strength (backscatter) from radar, newer methods of radar interferometry using the correlation between two images taken from slightly different positions have been used to estimate vegetation height. Combining several wavelengths works particularly well, because longer wavelengths penetrate into the canopy more than shorter ones. Together with allometric equations, these image products can be used to produce biomass maps (Balzter et al. 2007).

(d) Models

Models are used to extrapolate biomass estimates over time and/or space from a limited (*in situ* or remotely sensed) dataset. These are generally empirical models based on a network of repeatedly measured sample plots, which may have biomass estimations built in or may require allometric relationships to convert volume to biomass. Because such models do not exist for most forested areas, process models that are based on multiple environmental variables and are calibrated to account for different vegetation types may be optimal (Australian Greenhouse Office, 1999).

Global Dynamic Vegetation Models are also being used to estimate biomass. However, because of model assumptions and simplifications the outcomes are not generally suitable to accurately represent the state of biomass distribution. These models are more suitable to run in conjunction with climate models.

One simple, yet rather uncertain approach, is provided by the IPCC guidelines for Land Use, Land-Use Change and Forestry (LULUCF). The Tier 1 method to estimate biomass uses a standardized eco-climatic stratification and regional default values to generate approximate biomass estimates that may be used when no other information is available, i.e. in some developing countries.

Currently, the monitoring of biomass depends primarily on in situ inventory information, even at regional and global levels. Remote sensing data can support inventory approaches by informing on current conditions, stratification, and changes in forests.

3.1 *In situ* measurements

In situ measurements can generally measure biomass with accuracy from 20% to 2%, depending on the geographical scale. They should be conducted no longer than every five years, in order to estimate biomass changes in time.

In situ measurements are critical to the monitoring of terrestrial carbon stocks. If optimised from scope of generated information, time and cost point of view, this method can be cost effective for the quality of the produced estimate on carbon. In-situ measurements can be carried out on timber and non-timber exploitation sites on basis of reprehensive sample of the total population at large scale. Nowadays, statistical methods and techniques of estimation of total living or dead woody volume and available conversion factors make it relatively easy to estimate living and dry biomass and carbon. Focussing on biomass and carbon estimates in a national survey imposes a number of limitations, particularly the low justification for countries to undertake a costly national biomass inventory. In order to optimise the cost, countries privilege integrated and wide-encompassing national forest inventories (FAO NFMA[1], 2008).

Biomass estimates based on forest inventories and biomass equations are more accurate than estimation derived from regional or global conversion and expansion factors. Due to their relatively low accuracy, estimates based on conversion and expansion factors are not appropriate for assessing changes in specific ecosystems. Estimating changes in forest biomass between two points in time presents particular considerations in regards to accuracy. Implementing permanent sample plots for forest inventories improves the precision of stock change measurements, by decreasing the margin of errors.

Many developed countries have forest inventories containing large numbers of sampling locations for decades (Sohngen et al., 2005), but many forest biomes elsewhere have little or no inventory data (IGOS, 2004; GCOS, 2003). Fortunately forestry information in developing countries has been improved and will continue to improve: in the last decade FAO assisted many countries to set up national forest assessment and monitoring systems based on harmonised approach. Countries with existing forest biomass inventories use these as the basis of their forest resource reporting to the UNFCCC. In the past, the biomass inventories have generally been developed for forestry and agricultural purposes (not for carbon measurement) at the national and sub-national levels, and there were less efforts to coordinate and harmonize these inventories internationally. As a result, there was a high degree of inconsistency among the inventories with regard to definitions, standards, type of data collected, and quality (IGOS, 2004). Among the available global gridded biomass data set is that from the World Resources Institute, based on existing databases supplemented by satellite observations. The accuracy, resolution and currency of this data set are unknown (GCOS, 2003). Most detailed *in situ* above-ground biomass data are now readily available in a number of countries (e.g. Philippines, Cameroon, Bangladesh, Costa Rica, Guatemala, Honduras, Nicaragua and Zambia) and will soon be available in other countries like Congo, Angola, Tanzania, Kenya, Vietnam, Ecuador, Peru, etc.. Country-by-country summary statistics are available, published by the FAO in their Forest Resources Assessments, but biases and uncertainties in these summary values have not been quantified (FAO, 2006).

Assessment of below-ground biomass is particularly challenging because (as it cannot be measured from satellites), it requires an increased density of *in situ* observations and improved scaling algorithms (FAO, 2001). There is also the global inventory providing below-ground biomass information by the FAO/UNESCO soil map of the world (based on soil surveys performed in the 1960s). Several regional updates of the map have been undertaken using the SOTER approach (FAO, 2001).

Dead pools are also important to quantify

1 Report of International Expert Consultation on National Forest Monitoring and Assessment (NFMA): Meeting Evolving Needs

annual net carbon uptake, which simplifies the difference between net primary production (change in live biomass) and heterotrophic respiration from change in carbon pools in soil and dead matter. Thus, measurements are needed on soil carbon, biomass of coarse and fine woody debris and litter mass (Hairiah et al., 2001; Law et al. 2003). Pools of dead organic matter are also needed to determine if there are changes in mortality rates with climate or disturbance over the long-term.

With the rising importance and increasing sophistication of satellite methods for biomass estimation, *in situ* methods remain important as a means of "ground truth" for satellite measurements. As such, in order to improve accuracy and provide internal validation, *in situ* biophysical and socio-economic data collection is being integrated with remote-sensing observations under the National Forest Assessment and Monitoring programme of FAO

This is particularly important with coarse spatial resolution satellite data (e.g. 1 km resolution), where the field sampling strategy would support the accurate estimate of the biomass density within the remote sensing observation unit (pixel).

In any case, the ground-based national forest inventories currently contain the most accurate biomass estimates, suited for reliable assessments of biomass changes and GHG emissions both at national and global scale. Unfortunately biomass equations only give accurate estimates as long as they are applied to the same population from which the sample trees or plots were taken. If management practices change, the estimates may become biased when the change in forest characteristics is not appropriately reflected in the models used to estimate biomass.

3.2 Satellite Observations

Satellite technology allows for increasingly frequent measurement of biomass. Satellites sample with varying time frequencies (e.g. days, weeks, months), but temporal sampling points throughout the year should be compared with at least yearly repetition. Satellite approaches to estimating biomass are still in experimental stages and pre-operational, with uncertain accuracy. However, several methods using satellite data have demonstrated potential for providing direct and indirect global above-ground biomass information at high resolution (below 1 km), and will become increasingly important for biomass monitoring (TEMS[2] ; IGCO, 2004; GCOS, 2003).

The direct approach infers biomass directly from the spectral signal, while the indirect approach measures forest height or another variable and applies an allometric relation to arrive at a biomass estimate (e.g. Hall et al., 2006).

The strong correlation between spectral data and vegetation parameters, the repetitiveness of data collection and the availability of global coverage are in favour of the use of remote sensing for biomass estimation over large areas, especially in remote places (Lu, 2006).

The Integrated Global Carbon Observations Implementation Plan (IGCO, 2004) identifies three remote-sensing technologies that are especially promising for obtaining data that can contribute to improved biomass estimates:

1. Long-wavelength radar instrument has proved to be useful for estimating and mapping biomass of several forest biomes. The ALOS L-band Synthetic Aperture Radar (SAR, launched in early 2006) builds on the JERS-1 L-band SAR technology (used for tropical and boreal forest monitoring during its lifetime) and should provide the first systematic global observations for generating biomass maps. The temporal and spatial resolution, and the conditions of observation (e.g. incident angle), however, can be different from one satellite to another. Currently, the lowest frequency that

2 www.fao.org/gtos/tems/variable_list.jsp

can be used for spaceborne SAR is P-band (i.e. for the planned ESA-BIOMASS mission). P-band backscatter has been shown to be sensitive to forest biomass up to a saturation level of 100-300 t/ha (depending on forest type), making it suitable to map the biomass of most of the boreal forest and a large part of the temperate forests (but not the biomass levels found in the tropics) (GCOS, 2003; IGCOS, 2004). The saturation of radar backscatter alone at higher levels of biomass is a known limitation of these technologies. L-band SAR can provide high spatial resolution maps of deforestation, and consequently it is more sensitive to biomass removal and can be useful for estimating biomass losses from deforestation. However, advanced SAR technologies, i.e. integration of multi-temporal observations (Kurvonen et al., 1999), interferometric SAR using C-, L-, and P-band (Askne et al., 2003; Wagner et al., 2003; Treuhaft et al. 2004; Balzter et al., 2007a), and very high frequency SAR, while currently limited to airborne sensors (Fransson et al., 2000) have demonstrated further potential for forest biomass mapping up to at least 200 m3/ha (Santoro et al., 2006).

2. Indirect methods measure forest height and apply local or regional allometric relationships to estimate biomass: Airborne LiDAR systems and polarimetric SAR interferometry. Airborne imaging LiDAR produces spatial maps while profiling LiDAR produces a series of 3-dimensonal profiles through the vegetation layer at equally spaced positions along the orbits. Imaging LiDAR-derived vegetation height maps can be used to generate biomass maps (Patenaude et al., 2004; Balzter et al., 2007b). LiDAR technologies are currently limited to airborne sensors, except for the ICESAT-GLAS satellite sensor that can provide a full waveform for each imaged footprint, which can give estimates of vegetation canopy height (Harding and Carabajal, 2005; Lefsky et al., 2005) that then need to be spatially extrapolated. SAR technologies were first used for the generation of spatial maps of forest biomass estimates in the SIBERIA project (Balzter et al. 2001, Wagner et al. 2003), which used three radar satellites (ERS-1, ERS-2 and JERS-1) to map million km2 of Siberian forest from space exploiting two different wavelengths (C- and L-band) and SAR interferometry (C-band). Airborne SAR data have shown that dual-wavelength SAR interferometry has the potential to generate tree height maps (Balzter et al., 2007a; Rowland and Balzter, 2007). In any case, L-band SAR polarimetric interferometry provides more rigorous measurement of biomass than C-band, although it is still limited to 50-70 t/ha and therefore most suitable for mapping the biomass of low productivity or young forests (IGCOS, 2004; IGOS, 2004; FAO, 2001).

3. Among the direct approaches, optical data (Landsat ETM, MODIS, MERIS, SPOT) have also been widely used for biomass estimation with different quality results (Lu, 2006). There are a multitude of methods that can be used with these optical data sources, and the method applied tends to be driven by available data sources from which to estimate biomass from models that are based on remote sensing observations. Optical data at medium-high spatial resolution (e.g. Landsat ETM+, 30 m resolution) can provide data to undertake a spatial stratification of vegetation from which estimates of biomass distribution can be generated. In contrast, data at medium-coarse resolution (e.g. MODIS, 500 m / 1 Km resolution) can be useful for studies at regional to continental scale because their high temporal frequency increases the probability of acquiring cloud-free data for generating consistent datasets over large areas. The non-linear relationship between

biomass and optical spectral bands (Baccini et al., 2004) suggests the use of non-parametric empirical models as tree-based algorithms or neural networks, when sufficient field data are available. Recent studies have achieved promising results using tree-based models and metrics derived from MODIS data, in combination with radar data and ancillary information (climate, topography and vegetation maps), to map the biomass distribution for the Amazon basin (Saatchi et al., 2007), the United States (Blackard et al., 2008) and tropical Africa (Baccini et al., 2008). This approach is usually limited by the saturation of spectral data at high biomass density and by the mismatch between the size of field plots and pixel size. Also, transferability of empirical models among biomes is problematic. Determining the optical data source to employ should, in part, be driven by the scale desired for assessment and reporting in addition to available data sources. The timing for data reporting may also influence the combinations of field and remote sensing data sources that may be employed. Depending on the resolution of data sources employed, satellite estimates of biomass does tend to be more suited towards a regional estimation of its relative magnitude and spatial distribution than it does for precise, local estimates at a defined location.

3.3 Summary of requirements and gaps

IGOS (Integrated Global Observing Strategy) and its carbon theme (IGCO, Integrated Carbon Observation System) is seeking to make a coordinated system of integrated global carbon cycle observations operational by 2015, through the harmonization of existing components and the development of new components. The new IGCO document should be produced by 2011 as a GEO component. The programme seeks to collaborate with national forest inventory programmes, harmonize the data from various countries, and to report them in a transparent and verifiable manner to form an internally consistent global dataset for carbon accounting purposes. Over land, the carbon observing system will make repeat measurements (at 5-year intervals) of above-ground biomass in sample plots in all major forest biomes including both unmanaged and managed forests in the tropics, the temperate and boreal zones (IGOS, 2004).

Efforts to create continuous, standardized, geo-referenced forest biomass inventories will require harmonizing the widely varying methodologies for data collection and analysis. The standard methodology for biomass values for use in grid cells should include:

- Probability-based sampling across regions (e.g. systematic grid design)
- Minimum, maximum, mean, median, standard deviation, estimation protocol, number of points included (e.g. variable radius subplots in forests adjusted to maximum coefficient of variation <20%);
- Biomass by stem wood, root, foliage, and branch components; coarse woody debris, fine woody debris, litter mass to characterize dead mass pools and heterotrophic respiration;
- Time period represented by the biomass estimates (IGCOS, 2004).

For remote sensing based biomass estimation, the adoption of a single land classification system, such as the Land Cover Classification System (LCCS), would increase the consistency among measurements and enhance standardization efforts. LCCS was submitted for approval to become an international standard through the TC 211 technical committee of the International Organization for Standardization (ISO). Moreover it is in the process of being linked to designated biomass values that will allow for automatic biomass estimates by land cover type (FAO, 2005).

In countries where other land cover classification systems may be in operation, translation systems would be needed to facilitate translation to the LCCS. The definition of standard biomass data products from L-band SAR is also desirable.

Another major observational challenge is to develop more allometric functions to estimate biomass from diameter, height and wood density in a range of vegetation types, climate zones, and fertility classes (e.g. yield classes based on age-height relations). Allometirc functions should include the total volume of stump, stem and branch wood. Allometric functions are also needed in a similar range of conditions to convert above-ground biomass to total biomass (IGOS, 2004).

Regional or national biomass conversion and expansion factors (BCEF) and biomass/carbon conversion factors are also needed. Conversion factors for computing carbon from biomass of foliage, root, and wood components are needed in a global library. Individual studies have measured carbon content of these pools, but this is not broadly measured and compiled in one database. Some networks are beginning to compile these data (e.g. AmeriFlux, http://public.ornl.gov/ameriflux/).

There is a need to consider the accuracy of the generated biomass maps and particularly at national levels or at large spatial scales. The accuracy of biomass estimates is notably influenced by the spatial resolution, currency, accuracy and precision of the input data sources. As a result, the accuracy of a biomass estimate at one location may not be equivalent at those at another location. Methods are needed that can quantify or qualify the level of uncertainty in biomass estimates.

4. Contributing networks and agencies

The Food and Agriculture Organization of United Nations (FAO).

The Global Terrestrial Observing System (GTOS) and its Panels on Land Cover (GOFC-GOLD - Global Observations of Forest Cover and Land Dynamics), Carbon (TCO - Terrestrial Carbon Observations) and Climate (TOPC - Terrestrial Observation Panel for Climate).

FluxNet: Carbon Flux Networks are converging on data collection, submission and data management protocols. They collect data on forest biomass, productivity, and carbon and nitrogen content of biomass components in addition to ecosystem fluxes. The networks include AmeriFlux, Afriflux, AsiaFlux, CarboAfrica, CarboEurope, ChinaFlux, the Canadian Carbon Program, KoFlux, and OzFlux. For example, AmeriFlux developed biological data collection and submission protocols and they have been adopted by CarboEurope and proposed as global protocols as an activity of the GTOS TCO panel (Law et al., 2008).

5. Available data

Most countries have operational methodologies for woody biomass inventories, typically using field-based surveys, or a combination of remote sensing and field-based observations. Such national data typically form the basis for the annual reporting on forest resources (i.e. in the context of the UNFCCC).

In contrast, biomass information is uncertain for many developing countries, which are often those undergoing the fastest rates of deforestation. National inventories differ greatly in definitions, standards and quality, and the detailed information available at national level is normally unavailable internationally.

Some regional harmonization efforts, such the European Forest Inventory, lead to improved regional information. Nevertheless, biases and uncertainties in these summary values are not quantified.

At the global level, FAO regularly monitors the world's forests through a Global Forest Resources Assessment. It is based on countries' reports and remote sensing assessment at sampling sites. FAO also conducts land cover mapping in developing countries based on remote sensing and using the Land Cover Classification System (LCCS).

5.1 *In situ*

There are number of initiatives and networks that undertake *in situ* measurement initiatives. Many of these networks can be viewed in the Terrestrial Ecosystem Monitoring Sites (TEMS) database, an international directory of sites and networks that carry out long-term, terrestrial *in situ* monitoring and research activities.

5.2 Satellite

The potential for estimating biomass from space has been demonstrated in a number of research projects. However, improvement, development and implementation of approaches that integrate field and satellite-based observations for the estimation of biomass are required. In remote northern regions, there has been encouraging results from integrating and scaling field, high and medium spatial resolution satellite data for biomass estimation and mapping. Remote observations (combined with *in situ* data) may be particularly useful in developing countries where the largest uncertainties in biomass estimates and carbon sequestration or loss exist. Particular direct biomass estimation potentials result from vegetation LiDAR observation. In addition, the JAXA ALOS-PALSAR L-band (24 cm wavelength) satellite radar currently in orbit should be able to supply information on the lower range of biomass (up to 50-80 t/ha). The BIOMASS mission currently under study for launch around 2014 by ESA uses a longer wavelength (68 cm) that should be able to sense higher levels of biomass.

The NASA DESDynI satellite mission combines an active SAR and LiDAR and is planned for 2015.

6. Other issues

There is a worldwide lack of funding, personnel resources and mandate for a concrete and useful biomass monitoring at the global scale. Resources are required to maintain and extend *in situ* capabilities and space-based observation assets to make available baseline data of worldwide consistency and availability. Commitments and Capacities particularly need to be built in developing countries. International cooperation and communication on biomass monitoring is required to standardize methodology, provide effective technology transfer and advisory services to developing countries, and coordinate national efforts, in order to develop long-term continuity and consistency in worldwide biomass monitoring.

There is a need to define a base year for reporting and a time period where a new assessment would be necessary. In between these years, a system for accounting for the major changes to biomass carbon stocks and changes could be employed such as from incorporating the effects of disturbances.

There is also a need to maintain databases over the long-term so these rich data sources are available to the large global user group into the future. Data management commitments will vary by country or program.

7. Conclusions

There are large gaps in available data on biomass in terms of inclusion of above and below-ground components, live and dead components including soil, spatial and temporal consistency, and completeness in both spatial and temporal dimensions (FAO, 2001). The *in situ* inventory agencies and remote sensing agencies must work together to allow validation and upscaling of the *in situ* measurements based on the remote sensing products (IGCOS, 2004).

To increase the quantity of below-ground biomass observations, new soil carbon estimation techniques must be developed that combine *in situ* and modelling strategies.

Though still under development, satellite-based methods are very important for quantifying above-ground biomass and its changes at high spatial resolution. The most promising of these are long-wavelength radar, LiDAR and radar interferometric techniques, and results from integrating and scaling in-situ with multi-sensor, multi-resolution satellite sensors.

The integration of field, remote sensing data and models provides the most feasible approach by which biomass can be mapped at large spatial scales. Within this framework, methods are needed to assess the degree of uncertainty of these biomass estimates as they are fundamental when providing input to models that assess changes in carbon and carbon stocks over time as a result of deforestation, afforestation, natural disturbances and other factors that may result in changes to the forest landscape.

8. Recommendations

8.1 Standards and methods

1. *In situ* measurements for biomass should be conducted at least every 5 years, and remote sensing inference should be repeated at least on an annual basis. The annual basis should be focused on incorporating natural disturbance effects as an update to existing biomass estimates.
2. Follow the IPCC Guidelines for National Greenhouse Gas Inventories (Vol.4, Agriculture, Forestry and Other Land Use), 2006, for standard *in situ* biomass measurements, especially if countries do not have any better regional or national conversion factors or biomass equations.
3. Promote the development of new standards for biomass products (that may integrate different methods and data sources, i.e. *in situ* and remote sensed) used in biomass estimation and mapping over large geographic areas. Current different methodologies for data collection and analysis of continuous, standardized and geo-referenced forest biomass inventories should be harmonized.
4. Improve the quality and quantity of *in situ* biomass estimates needed for remote sensing calibration and validation; develop the required international validated methodology for biomass estimation from remote sensing.
5. Develop methods for assessing uncertainty of biomass estimates and maps, in order to provide more reliable inputs to models for assessing and monitoring changes in carbon and carbon stocks over time.
6. Extend forest biomass inventories to tropical forests, non-commercial forests, mangroves, dry woodlands and under-represented regions, and increase the number of permanent plots and the periodicity of data collection.

7. Develop new or improved allometric functions (in a range of vegetation types, climate zones, and fertility classes) with associated description of the site chacteristics (e.g. soil, climate, etc.) where the allometric functions were derived in order to make them of independent value and applicable to wider geographic area, along with an analysis of the error propagation effects that may occur during the scaling process.
8. Develop better and validated regional or national biomass conversion and expansion factors and carbon conversion factors. Conversion factors for computing carbon from biomass of foliage, root, and wood components are needed in a global library. Individual studies have measured carbon content of these pools, but this is not broadly measured and compiled in one database. Some networks are beginning to compile these data (e.g. AmeriFlux, http://public.ornl.gov/ameriflux/).
9. More coordination is needed among the *in situ* and space based earth observation communities to move remote sensing assessments for biomass mapping to more operational mode. Agencies with *in situ* inventories and remote sensing data should be encouraged to work together to allow validation and up scaling of *in situ* measurements.
10. Pursue a further development and integration of SAR and optical data to provide estimates of biomass in a synoptic manner over large areas and explore the possibility of defining standard biomass data products from active remote-sensing methodologies, such as SAR or LiDAR.
11. Produce more accurate tree height measurements from LiDAR technology, calibrated with field samples (i.e. field laser), in order to improve the biomass estimates derived from allometry and the methods to incorporate these datasets into regional estimation and mapping. Mechanisms are needed for increased acquisition and availability of LiDAR data over large geographic areas. Because of cost and data volumes incurred in LiDAR acquisition missions and the availability of spaceborne large-footprint LiDAR, considerations to sampling strategies to statistically represent different ecozones merit investigation.
12. Full advantage should be taken of existing and planned satellite SAR missions including historical data (JERS-1, ERS-1/2 interferometry), current sensors (multitemporal ENVISAT-ASAR, ALOS-PALSAR) and support future missions (ALOS follow up, ESA-BIOMASS).
13. For a more comprehensive picture of the total biomass in a stand, below ground biomass, coarse woody debris, fine woody debris and litter mass should be also considered, and new soil carbon measurement techniques and sampling strategies should be developed. In particular the density and the spatial coverage of *in situ* observations of below-ground biomass should be improved i) by improving or adding observations within existing networks; ii) by significantly expanding the soil profile databases available through SOTER and similar programmes; and iii) through more efficient use of national inventories, in combination with land cover derived from satellite data. Deployment of biomass surveys to obtain full coverage of forest ecosystems, particularly in the tropics, is necessary. Also the fractal methods (van Noordwijk and Mulia, 2002) should be better investigated.
14. *In situ* measurements for biomass should be conducted at least every 5 years, and remote sensing inference should be repeated at least on an annual basis. The annual basis should be focused on incorporating natural disturbance effects as an update to existing biomass estimates.
15. A single classification system for remote sensing estimation of biomass should be adopted; a widely accepted standard is the Land Cover Classification

System (LCCS) and its accepted translations for countries.

No international validated standards are already available for biomass estimation from remote sensing.

8.2 Other recommendations

- Increase funding.
- Develop capacities (especially in developing countries).
- Encourage and foster mandate at the highest governmental levels that could translate into increased resources and capacity.
- Increase the support to the international efforts to coordinate and harmonize national forest and biomass inventories
- Coordinate and maintain databases relevant to biomass over the long-term so these rich data sources are available to the large global user group into the future. Data management commitments should vary by country or program.

References

- **Askne, J., Santoro, M., Smith, G. and Fransson, J.E.S.** 2003. Multitemporal repeat-pass SAR interferometry of boreal forests. *IEEE Transactions on Geoscience and Remote Sensing*, **41**, 1540-1550.
- **Australian Greenhouse Office,** 1999. National Carbon Accounting System, Methods for Estimating Woody Biomass. *Technical Report* No. 3, Commonwealth of Australia.
- **Baccini, A., Friedl, M.A., Woodcock, C.E. and Warbington, R.** 2004. Forest biomass estimation over regional scales using multisource data. *Geophys. Res. Lett.*, **31**, L10501
- **Baccini, A., Laporte, N., Goetz, S., Sun, M. and Dong, H.** 2008. Mapping tropical Africa above-ground biomass using satellite data. *Proceedings of the 2008 IEEE International Geoscience & Remote Sensing Symposium*, July 6-11, 2008, Boston (MA) U.S.A (also available at www.igarss08.org/Abstracts/pdfs/4172.pdf)
- **Balzter, H., Luckman, A., Skinner, L., Rowland, C. and Dawson, T.** 2007b. Observations of forest stand top height and mean height from interferometric SAR and LiDAR over a conifer plantation at Thetford Forest, UK, *International Journal of Remote Sensing*, **28**:6, 1173 - 1197.
- **Balzter, H., Rowland, C.S. and Saich, P.** 2007a. Forest canopy height and carbon estimation at Monks Wood National Nature Reserve, UK, using dual-wavelength SAR interferometry, *Remote Sensing of Environment*, **108**, 224-239.
- **Balzter, H., Talmon, E., Wagner, W., Gaveau, D., Plummer, S. and Yu, J.J. Quegan, S., Davidson, M., Le, Toan T., Gluck, M., Shvidenko, A., Nilsson, S., Tansey, K., Luckman, A. and Schmullius, C.** 2002. Accuracy assessment of a large-scale forest map of Central Siberia from Synthetic Aperture Radar. *Canadian Journal of Remote Sensing*, **28**, 719-737.

- **Blackard, J.A., Finco, M.V., Helmer, E.H., Holden, G.R., Hoppus, M.L., Jacobs, D.M., Lister, A.J., Moisen, G.G., Nelson, M.D., Riemann, R., Ruefenacht, B., Salajanu, D., Weyermann, D.L., Winterberger, K.C. Brandeis, T.J., Czaplewski, R.L., McRoberts, R.E., Patterson, P.L. and Tymcio, R.P.** 2008. Mapping U.S. forest biomass using nationwide forest inventory data and moderate resolution information. *Remote Sensing of Environment,* **112**:4, 1658-1677
- **Case, B.S. and Hall, R.J.** 2008. Assessing prediction errors of generalized tree biomass and volume equations for the boreal forest region of West-Central Canada. *Canadian Journal of Forest Research,* **38**, 878-889.
- **Chave, J., Andalo, C., Brown, S., Cairns, M.A., Chambers, J.Q., Eamus, D., Fölster, H., Fromard, F., Higuchi, N., Kira, T., Lescure, J.P., Nelson, B.W., Ogawa, H., Puig, H., Riera, B. and Yamakura, T.** 2005. Tree allometry and improved estimation of carbon stocks and balance in tropical forests. *Oecologia* **145**, 87-99
- **FAO,** 2001. Terrestrial Carbon Observation: The Rio de Janeiro recommendations for terrestrial and atmospheric measurements. *Environment and Natural Resources Series,* No. 3, Rome.
- **FAO,** 2005. Land Cover Classification System: Classification concepts and user manual. *Environment and Natural Resources Series*, No. 8, Rome.
- **FAO,** 2006. Global forest resources assessment 2005: progress towards sustainable forest management. *FAO Forestry Paper,* 147, Rome.
- **FAO-FNAM,** 2008. *Report of International Expert Consultation on National Forest Monitoring and Assessment (NFMA): Meeting Evolving Needs,* Rome.
- **Fransson, J.E.S., Walter, F. and Ulander, L.M.H.** 2000. Estimation of forest parameters using VHF SAR data. *IEEE Transactions on Geoscience and Remote Sensing,* **38**, 720-727.
- **GCOS,** 2003. The Second Report on Adequacy of Global Observation Systems for Climate in Support of the UNFCCC. Global Climate Observing System, *Report GCOS*-82. FAO, Rome.
- **GCOS,** 2006. Systematic observation requirements for satellite-based products for climate. Supplemental details to the satellite-based component of the "Implementation Plan for the Global Observing System for Climate in Support of the UNFCCC", *Report GCOS*-107 (WMO/TD No. 1338). FAO, Rome, 90pp.
- **Graetz, R.D.** 1998. The Terrestrial Carbon Pools of the Australian Continent: an Assessment of their Size, Dynamics, and Tractability. *Unpubl. Report* to National Greenhouse Gas Inventory, Environment Australia, Canberra. 245 p.
- **Gullison, R.E., Frumhoff, P.C., Canadell, J.G., Field, C.B., Nepstad, D.C., Hayhoe, K., Avissar, R., Curran, L.M., Friedlingstein, P., Jones, C.D. and Nobre, C.** 2007. Tropical Forests and Climate Policy, *Science,* **316**, 985-986.
- **Hairiah, K., Sitompul, S.M., van Noordwijk. M. and Palm, C.A.** 2001. Methods for sampling carbon stocks above and below ground. *ASB Lecture Note* 4B. International Centre for Research in Agroforestry, SEA Regional Research Programme, Bogor, Indonesia, 23pp.
- **Hall, R.J., Skakun, R.S., Arsenault, E.J. and Case, B.S.** 2006. Modeling forest stand structure attributes using Landsat ETM+ data: *Forest Ecology and Management,* **225**, 378-390.
- **Hamburg, S.P., Zamolodchikov, D.G., Korovin, G.N. Nefedjef, V.V., Utkin, A.I., Gulbe, J.I., Gulbe, T.A.,** 1997. Estimating the carbon content of Russian forests; a comparison of phytomass/volume and allometric projections. *Mitigation and Adaptation Strategies for Global Change,* **2**:2-3, 247-265.
- **Harding, D.J. and Carabajal, C.** 2005. ICESat waveform measurements of within-footprint

topographic relief and vegetation vertical structure. *Geophysical Research Letters,* **32**, L21S10.

- **Harrell, P.A., Bourgeau-Chavez, L.L., Kasischke, E.S., French, N.H.F. and Christensen, N.L.** 1995. Sensitivity of ERS-1 and JERS-1 RADAR data to biomass and stand structure in Alaskan boreal forest. *Remote Sensing of Environment,* **54**, 247-260
- **Heiskanen, J.** 2006. Estimated aboveground tree biomass and leaf area index in a mountain birch forest using ASTER satellite data. *International Journal of Remote Sensing,* **27**, 1135-1158.
- **IGCOS,** 2004. *Integrated Global Carbon Observation Theme: A Strategy to Realise a Coordinated System of Integrated Global Carbon Cycle Observations.* FAO, Rome.
- **IGOS,** 2004. *Integrated Global Carbon Observation System. Implementation Plan.* Draft 1.0. FAO, Rome.
- **IPCC,** 2003. *Good Practice Guidance for Land-Use, Land-Use Change and Forestry.* Institute for Global Environmental Strategies, Kanagawa, Japan
- **IPCC,** 2006. *Guidelines for National Greenhouse Gas Inventories,* Vol.4 AFOLU (Agriculture, Forestry and Other Land Use), Kanagawa, Japan (Also available at http://www.ipcc-nggip.iges.or.jp/public/2006gl/vol4.html).
- **Isaev, A.S., Korovin, G.N., Bartalev, S.A., Ershov, D.V., Janetos, A., Kasischke, E.S., Shugart, H.H., French, N.H.F., Orlick, B.E. and Murphy, T.L.** 2002. Using remote sensing to assess Russian forest fire carbon emissions. *Climatic Change,* **55**, 235-249.
- **Kurvonen, L., Pulliainen, J. and Hallikainen, M.** 1999. Retrieval of biomass in boreal forests from multitemporal ERS-1 and JERS-1 SAR images. *IEEE Transactions on Geoscience and Remote Sensing,* **37**, 198-205.
- **Kurz, W.A., Stinson, G., Rampley, G., Dymond, C.C. and Neilson, E.T.** 2008a. Risk of natural disturbances makes future contribution of Canada's forests to the global carbon cycle highly uncertain. *Proceedings of the National Academy of Sciences (USA),* **105**, 1551-1555.
- **Kurz, W.A., Stinson, G., Rampley, G., Neilson, E.T., Carroll, A.L., Ebata, T. and Safranyik, L.** 2008b. Mountain pine beetle and forest carbon feedback to climate change. *Nature,* **452**, 987-990.
- **Lambert, M. C., Ung, C. H. and Raulier, F.** 2005. Canadian national tree aboveground biomass equations. *Canadian Journal of Forest Research,* **35**, 1996-2018.
- **Law, B.E., Campbell, J.L., Sun, O., van Ingen, C. and Verma, S.** 2008. Terrestrial Carbon Observations: Protocols for Forest Sampling and Data Submission. FAO, *GTOS Publication Series* N.52, Rome, 79 pp.
- **Law, B.E., O. Sun, J. Campbell, S. Van Tuyl, P. Thornton.** 2003. Changes in carbon storage and fluxes in a chronosequence of ponderosa pine. *Global Change Biology,* **9**, 510-524.
- **Lefsky, M. A., Harding, D.J., Keller, M., Cohen, W. B., Carabajal, C. C., Del Bom Espirito-Santo F., Hunter, M. O. and de Oliveira Jr. R.** 2005. Estimates of Forest Canopy Height and Aboveground Biomass using ICESat. *Geophysical Research Letters,* **32**, L22S02.
- **Lu, D.** 2006. The potential and challenge of remote sensing-based biomass estimation. *International Journal of Remote Sensing,* **27**:7, 1297–1328
- **Patenaude, G., Hill, R.A., Milne, R., Gaveau, D. L. A., Briggs, B. B. J. and Dawson, T.P.** 2004. Quantifying forest above ground carbon content using LiDAR remote sensing. *Remote Sensing of Environment,* **93**:3, 368-380.
- **Ravindranath, N.H. and Ostwald, M.** 2008. Carbon inventory methods – handbook for greenhouse gas inventory, carbon mitigation and roundwood production projects. *Advances in Global Change Research,* Springer Verlag, pp 304.
- **Rowland, C. and Balzter, H.** 2007. Data fusion for reconstruction of a DTM from L-band airborne

InSAR under semi-natural, deciduous woodland, *IEEE Transactions on Geoscience and Remote Sensing*, **45**:5, 1154-1163.

- **Saatchi, S.S., Houghton, R.A., Dos Santos Alvala, R.C., Soares, J.V. and Yu, Y.** 2007. Distribution of aboveground live biomass in the Amazon basin. *Global Change Biology*, **13**, 816–837
- **Santoro, M., Eriksson, L., Askne, J. and Schmullius, C.** 2006. Assessment of stand-wise stem volume retrieval in boreal forest from JERS-1 L-band SAR backscatter. *International Journal of Remote Sensing*, **27**: 3425-3454.
- **Satoo, T. and Madgwick, H.A.I.** 1982. *Forest Biomass*. Nijhoff, Den Haag, Amsterdam, 132 pp.
- **Schroeder, P., Brown, S., Mo, J., Birdsey, R. and Cieszewski, C.** 1997. Biomass estimation for temperate broadleaf forests of the United States using inventory data. *Forest Science*, **43**, 424-434.
- **Scurlock, J.M.O., Johnson, K. and Olson, R.J.** 2002. Estimating net primary productivity from grassland biomass dynamics measurements. *Global Change Biology*, **8**, 736–753.
- **Sohngen, B., Andrasko, K., Gytarsky, M., Korovin, G., Laestadius, L., Murray, B., Utkin, A. and Zamolodchikov, D.** 2005. *Stocks and flows: carbon inventory and mitigation potential of the Russian forest and land base.* World Resources Institute, Washington, 52 pp.
- **Treuhaft, R.N., Law, B.E. and Asner, G.P.** 2004. Forest attributes from radar interferometric structure and its fusion with optical remote sensing. *BioScience*, **54**, 561-572.
- **Turquety, S., Logan, J.A., Jacob, D.J., Hudman, R.C., Leung, F.Y., Heald, C.L., Yantosca, R.M., Wu, S., Emmons, L.K., Edwards, D.P. and Sachse, G.W.** 2007. Inventory of boreal fire emissions for North America in 2004: importance of peat burning and pyroconvective injection. *Journal of Geophysical Research*, **112**, D12S03, doi 10.1029/2006JD007281.
- **Van Noordwijk, M. and Mulia, R.** 2002. Functional branch analysis as tool for fractal scaling above- and below-ground trees for their additive and non-additive properties. *Ecological Modelling*, **149**:1-2, 41-51.
- **Wagner, W., Luckman, A., Vietmeier, J., Tansey, K., Baltzter, H., Schmullius, C., Davidson, M., Gaveau, D., Gluck, M., Le, Toan T., Quegan, S., Shvidenko, A., Wiesmann A. and Yu, J.** 2003. Large-scale mapping of boreal forest in Siberia using ERS tandem coherence and JERS backscatter data. *Remote Sensing of Environment*, **85**, 125-144.

Web sites

http://www.fao.org/

www.fao.org/gtos/tems/variable_list.jsp

http://www.fao.org/gtos/topcECV.html

http://www.fao.org/gtos/TCO.html

http://www.gofc-gold.uni-jena.de/sites/biomass.php

http://public.ornl.gov/ameriflux

http://daac.ornl.gov/NPP/npp_home.html

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